An Optimal Stopping Decision Method for Routing in Opportunistic Networks

Di Huang, Sanfeng Zhang, Zhou Chen

Abstract—**Delivery delay is an important performance metric in opportunistic networks. With given buffer size and copy numbers, how to select appropriate nodes to replicate message is the key to minimizing delivery delay. To solve this problem, this paper proposes an Optimal Stopping Decision method for Routing of opportunistic networks (OSDR). With OSDR, the average meeting time between a node and the destination is regarded as the forwarding utility of the node. A node carrying a message observes the random forwarding utilities of the nodes it meets, and replicates messages according to the optimal stopping rule, which turns out to be threshold-based. By making tradeoffs between the forwarding utility and waiting cost, OSDR achieves the minimum delivery delay expectation. This paper introduces the OSDR network model and existence proof and calculation of optimal stopping rule in detail. Simulation results show that OSDR outperforms other protocols in delivery delay and delivery rate.**

Index Terms—**Delivery Delay, Delivery Rate, Opportunistic Networks, Optimal Stopping**

I. Introduction

Wireless networks in forms of vehicular networks and sensor networks are often divided into several disconnected regions due to node mobility and energy constraint. Opportunistic Networks [1] are such kind of networks that can take advantage of meeting opportunities to delivery messages in split network conditions with a store-carry-and-forward mode, while traditional wireless multi-hop network protocols become unstable or even fail. A node will store a message if there is no next hop node and try to find appropriate forwarding opportunities with its mobility. Thus mobility modeling and routing methods are the key technologies of the opportunistic networks.

Most routing methods in opportunistic networks adopt redundancy mechanisms to improve delivery rate. In Epidemic [2] nodes carrying the message copy it to every node they meet. This method apparently consumes huge amount of buffer and causes a large number of communication overhead. To solve this problem, SprayAndWait (SAW) [3] controls the copies in the network by Tickets, which messages are only replicated limited times in disseminating stage. But the dissemination is blind as messages are just forwarded to first several nodes it meets without any selections. This will greatly degrade the network performance. Prophet [4] introduces the probability prediction mechanism to evaluate the forwarding utility, and it just forwards the message to the nodes that have better utility than itself. All these routing algorithms need buffer management mechanism to delete timeout or acked replicas. But deleting message may also result in the decrease of message delivery rate and the increase of delay. In a word, the number of message replicas and routing performance are two conflicting factors: larger number of replicas for a message can on the one hand lead to its higher delivery rate and lower delay; on the other hand, it may cause higher buffer cost and more message deleting operations. With limited message replicas, we can enhance network performance merely by maximizing the utilities of the selected nodes holding the message. Thus, the main problem in optimizing the routing method of opportunistic networks is how to choose the next-hop node and the forwarding opportunity so as to achieve higher delivery rate and lower delay with lower buffer cost and fewer transmission times.

In this paper we propose an Optimal Stopping Decision method for Routing of opportunistic networks (**OSDR**). By taking the optimal tradeoff between the average meeting time and waiting cost, OSDR can select the best time to stop observing and replicate the message to the node it meets, so as to achieve minimum average delay. Furthermore, due to the selection of high utilized nodes, OSDR can improve the delivery rate as well.

This paper is organized as follows: Section II introduces the network model and the routing framework of OSDR. Section III introduces the forwarding algorithm based on optimal stopping rule. Simulation and results are presented in section IV to prove the efficiency of our algorithm. In section V we introduce related works. Section VI concludes the paper.

II. Opportunistic Network Model And Routing Framework

A. Opportunistic network model

All nodes moving in a limited area, of which the number is *NUM*, constitute a node set *V*. Each node $i \in V$ is equipped with an omni-directional antenna. According to their given mobility

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model, nodes belong to different kind have different movement pattern but have the same communication distance. Nodes within each other's transmission range can only perform single-hop data transmission directly while indirect links of multi-hop do not exist. We suppose that all nodes have the same and constant bandwidth and they can generate messages with certain destination. Buffers of all nodes are the same and all messages are stored in it. Assume that the network runs by time slots with length of *T*. Nodes in idle channel inform others of its configuration information and detect the configuration of its neighboring nodes. We also suppose that two nodes can replicate all the messages which satisfy the forwarding policy when they meet with each other. Each message has two attributes: remaining hop count *H* and time-to-live *TTL*. When replication occurred in two nodes, both hop count of copies in these two nodes become *H-1*. If the *H* value in one replica decreases to *0*, the replica cannot be replicated by other nodes except for the destination node. *TTL* decreases with time slot and the message is deleted from the buffer if *TTL=0*.

B. Routing algorithm Framework

Node $i \in V$ checks the channel at each time slot and broadcasts a configuration message containing the node id *i* and an average meeting time vector $\overline{T_i} = (t_{i->1}, t_{i->2}, ..., t_{i->NUM})$, if the channel is empty. Variable $t_{i->d}$, $(d \in V)$ represents the average meeting time between *i* and *d.* If node $j \in V$ successfully receives the configuration message of node *i,* it will first update $t_{j->i}$ and $t_{i->\mathrm{j}}$ in the distance matrix $\overline{T}_{\mathrm{all}}$ (in every node, $\overline{T}_{\mathrm{all}}$ is a $NUM \times NUM$ matrix that records the entire average meeting times in the network): weighing $t_{j->i}$ and $t_{i->\mathrm{j}}$ according to average meeting time in history and the latest inter-meeting time. Then node *j* will replace the *i-th* row in $\overline{T}_{\mathrm{all}}$ with vector $\overline{T_i}$ and at last add $\overline{T_i}$ as a column to an observation matrix noted by $\overline{M_j}$. Every column in $\overline{M_j}$ denotes a vector received from a time-slot. Obviously the *d-th* row of $\overline{M_j}$ is the average inter-meeting time $t_{i->d}$ between *i* and *d* in all time slots. Node *j* regards all the $t_{i->d}$ as the observed values of T_d and fits a distribution of random variable T_d on these values for

$$\overline{T_{all}} \qquad \begin{bmatrix} 0 & t_{1->2} & \cdots & t_{1->NUM} \\ t_{2->1} & 0 & \cdots & t_{2->NUM} \\ \cdots & \cdots & 0 & \cdots \\ t_{NUM->1} & t_{NUM->2} & \cdots & 0 \end{bmatrix}$$

(a)

$$\overline{M_j} \qquad \begin{array}{c} \xrightarrow{\text{slots}} \\ \begin{bmatrix} 0 & t_{2->1} & \cdots \\ t_{1->2} & 0 & \cdots \\ \cdots & \cdots & \cdots \\ t_{1->NUM} & t_{2->NUM} & \cdots \end{bmatrix} \end{array}$$

(b)

Fig. 1. Data structures maintained by node *j*.

subsequent routing decision. Fig. 1 shows the data structures maintained by node *j*.

If node *j* receives a configuration message from *i* in some time slot, it will decide which messages to replicate to *i* according to the routing decision method based on the optimal stopping theory (OSDR). If node *j* copies the message with remaining hop *H* to *i* , hop count in both *i* and *j* will become *H-1*. If *H=0*, messages can only be copied to destination node d. Thus the maximum replicas of a message in the network are 2^H.

III. Optimal Stopping Decision method for Routing

High delivery rate and low average delay are two optimization objectives. Generally a higher delay may result in a lower delivery rate for an older replica is more likely to be deleted. We choose delivery delay as the optimization target, As described before, when node *j* receives the configuration message from *i* in slot *N,* it will decide whether to copy the message destined to *d* to *i* according to the observed value $t_{i->d}$. Two cases exist in the decision process: one is that $t_{x->d}$ of node *x* that it observes in the following time-slots are all larger than current observed value $t_{i->d}$, thus *j* should replicate the message to *i* immediately. The other case is that $t_{y->d}$ of node *y* it meets in time-slot *N+1* satisfies $t_{y->d} + T < t_{x->d}$, thus delivering this message to node *y* in slot *N+1* can get lower delay. Therefore, *j* needs to select appropriate slot to get lower delay. This problem can be modeled as an optimization of minimizing expected delivery delay.

As messages are copied among multiple nodes, nodes holding the message *m* form a node set V_m . So routing decision of node *j* ($j \in V_m$) aims to minimizing the expectation of minimum average delay ($E(\min_{s \in V_m \cup \{i\}} \{T_{s->d}\})$) in set $V_m \cup \{i\}$ destined to *d* by choosing a slot *N* and copying the message to *i* that *j* meets in *N.* We describe this problem as **MED** (Minimum Expected Delay) and solve it based on the optimal stopping rule.

A. Select forwarding slot using optimal stopping rule

For a sequence of random variables X_1, X_2, …, with a known joint distribution and reward functions: y_0, $y_1(x_1)$, $y_2(x_1,x_2)$, … , $y_\infty(x_1,x_2,\ldots)$. After observing $X_1=x_1$, $X_2=x_2$, … , $X_n=x_n$, we can either stop and receive the reward $y_n(x_1,x_2,\ldots,x_n)$, or continue to observe x_{n+1}. Optimal stopping rule choose a stopping time N^* to maximum the expected reward $E[Y_{N^*}]$.

For MED problem, the optimal rule is to choose a slot N^* to satisfy:

$$N^* = \arg E(\min_{N=0,1,2,\ldots} \{T_{s->d} \mid s \in V_m\} \cup \{N \cdot T + T_{i->d}\}) \qquad (1)$$

Or:

$$N^* = \arg \max_{N=0,1,2,\ldots} E(T_{s->d} - T_{i->d} - N \cdot T) \ , s \in V_m \qquad (2)$$

As above definitions, the mean inter-meeting time $T_{i->d}$ between *i* and *d* is the random variable, and $T_{s->d}$, $s \in V_m$ is known. For calculating convenience, we consider the node *s* observes itself and $T_{i->d} = T_{s->d}$ if no other node is observed in a time-slot. In addition, we believe that in most cases a node observes only one or zero node in a time-slot (This has been proved by the simulation results). Therefore we can select the best node whose $T_{i->d}$ is the smallest as the observed value for approximation if node observes several nodes.

Proposition 1

(a) MED problem exists stopping rule N^*, and

$$N^* = \min\{N \geq 1 : (T_{s->d} - T_{i->d}) \geq V^*\} \tag{3}$$

(b) V^* is the solution of the following equation：

$$E[T_{s->d} - T_{i->d} - V^*]^+ = T \tag{4}$$

[.]+ here means taking only positive ones. Proposition1 shows that messages can be replicated to current observed node if the observed value is within a range.

B. Existence proof and solutions of optimal stopping rule

We use optimal stopping theory to prove Proposition1. All theorems come from literature [5]. We define reward function:

$$Y_N = T_{s->d} - T_{i->d} - N \cdot T \ , \ N = 1,2,... \tag{5}$$

Description in II.A indicates that every node needs to probe at least one time if it wants to replicate the message to others. So N is a non-zero natural number. Next, we get the optimal rule through a general method.

First Step, prove the existence of Proposition1

According to theorem 3.1[5], optimal stopping rule exists when satisfying the following two conditions:

$$\begin{aligned} &\text{A1. } \mathrm{E}\{\sup_N Y_N\} < \infty \\ &\text{A2. } \lim \sup_{N->\infty} Y_N \leq Y_\infty \end{aligned} \tag{6}$$

From the definition of our reward function Y_N, we can easily find that $\lim \sup_{N->\infty} Y_N = -\infty$ and $Y_\infty = -\infty$. That is because $-N \cdot T -> -\infty$ when $N -> \infty$ and $(T_{s->d} - T_{i->d})$ has a range whose $\max(T_{s->d} - T_{i->d})$ and $\min(T_{s->d} - T_{i->d})$ exist and have specific values in a network. Therefore $\lim \sup_{N->\infty} Y_N \leq Y_\infty = -\infty$ and A2 is proved. Also, for any N=1, 2, 3, 4, … , $\sup_N Y_N < \infty$ so $\mathrm{E}\{\sup_N Y_N\} < \infty$ and A1 is proved. In summary, the reward function satisfies both A1 and A2. Therefore optimal stopping rule exist in our reward function.

Second Step, get the solutions of Proposition1

According to solutions to 4.1[5], we deduce the optimal stopping rules for our reward functions:

$$\text{Let} \qquad T_{s->d} - T_{i->d} = T_N \tag{7}$$

Let V^* denote the expected return of the optimal stopping rule. Suppose that a node pays T and T_1 is observed at first. If it continues from this point, T_1 will be lost and the node has to pay cost T again. It is like starting the problem again because the previous observed value will not have an influence on the next observation. That is also called the problem is invariant in time. Therefore, the principle of optimality (3.2 in [5]) says that if $T_N < V^*$, the node should continue observing, and if $T_N \geq V^*$ the node should stop and replicate. In this way, stopping rule becomes:

$$N^* = \min\{N \geq 1 : T_N \geq V^*\} \tag{8}$$

According to optimality equation (3.2 in [5]), solutions to stopping rule V^* are:

$$\begin{aligned} V^* &= E\max\{T_1, V^*\} - T \\ &= \int_{-\infty}^{V^*} V^* \cdot dF(t) + \int_{V^*}^{\infty} t \cdot dF(t) - T \end{aligned} \tag{9}$$

$$\text{Let} \quad V^* = \int_{-\infty}^{+\infty} V^* \cdot dF(t) \tag{10}$$

Combing (9) and (10):

$$\int_{-\infty}^{+\infty} V^* \cdot dF(t) = \int_{-\infty}^{V^*} V^* \cdot dF(t) + \int_{V^*}^{\infty} t \cdot dF(t) - T$$

$$\Rightarrow$$

$$\int_{-\infty}^{V^*} V^* \cdot dF(t) + \int_{V^*}^{\infty} t \cdot dF(t) - \int_{-\infty}^{+\infty} V^* \cdot dF(t) = T$$

$$\Rightarrow$$

$$\int_{V^*}^{\infty} (t - V^*) dF(t) = T \tag{11}$$

In these formulas, F represents the common distribution function of T_N.

For discrete variable $T_N = T_{s->d} - T_{i->d}$, we can deduce the following result by similar way:

$$E(T_N - V^*)^+ = T \tag{12}$$

So Proposition1 is proved.

C. Calculation methods for the threshold value V^*

There are two methods to calculate threshold V^*. The first one is to regard the T_N as discrete variable and use the formula (11). It just needs to sort all the possible values in descending order and tries each value interval to see if it satisfies (11). This will just cost O(n). The other one is to regard the T_N as continuous variable and use (10). We have to fit a curve and it is a little bit complex. So we adopt the first method.

D. Analysis for Assumptions of optimal stopping rule

When we use optimal stopping rule to solve MED problem, these assumptions must be met: random variables X_N (in our model $T_N = T_{s->d} - T_{i->d}$ are the random variables) must be independent identically distributed (i.i.d). There is a strong relationship among satisfaction degrees of the assumption and the granularity of time slot and mobility model: if node movement area is uniform (there are no such different types of area like urban and suburb) and node velocity fluctuate narrowly, random variables T_N tend to identical. If node movement range is large and time-slot granularity is big enough, T_N will have less relativity. For simplicity, we comprehensively consider time-slot granularity and movement area in our network to satisfy the i.i.d assumption. In practical applications, we can divide the area into several sub regions to enhance the satisfaction degree of this assumption. We will illustrate satisfactory situation with statistic data in experimental evaluation.

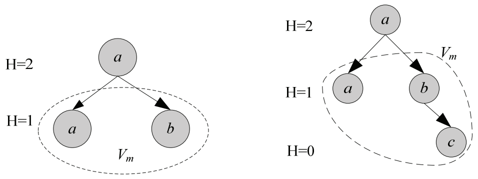
E. Analysis of message replication process

Based on the routing framework and the optimal stopping rule, OSDR works as follows:

In Fig. 2, If maximum hop H is limited to 2, the forwarding process is as following: $V_m = \{a\}$ when H=2, If in some time-slot node b satisfies formula (3) by calculation of formula

(4), a will replicate the message to b. And we must add the common distribution of $T_{i->d}$ to the message for the later calculation of V^* in formula (3) and (4). After this work done $V_m = \{a,b\}$ and *H=1*. Result is shown in Fig. 2(a). When b meets c, b will also determine whether to replicate or not. But this time OSDR need to update threshold V^* using the distribution of both a and b because there are two observation point (a and b) for the message in V_m. Both of these nodes can forward the message, so we can treat them equally and the equality lies in the $T_{i->d}$ distribution updating: replace it with an average on a and *b's* common distribution. If c gets the replica, results will be like Fig. 2 (b).

As Fig. 3 shows, if H is limited to 3, H equals to 1 after two

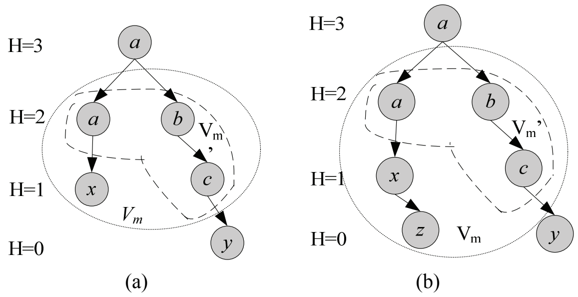


(a) (b)

Fig. 2. Replicating process when *H=2*.

replications and c meets y in some time slot. Following situation may exist in Fig. 3 (a): c knows $V_m' = \{a,b,c\}$ to be the set that holds the message replicas, but actually the set is $V_m = \{a,b,c,x\}$. Due to inaccurate knowledge in c, calculation using formula (4) for optimal stopping rule may lead to difference. This kind of difference grows as hop count increases. In Fig. 3 (b). V_m' has two fewer elements than V_m.

In conclusion, in H=2 condition, we can calculate all



(a) (b)

Fig. 3. Replicating process when *H=2*.

stopping moment accurately every time the node doing replication work according to (4), but this also limits the maximum number of replicas to four. When H>2 stopping rule calculation may be inaccurate due to lack of global knowledge of set V_m. In this process, we can see that it will have O(n) time cost if nodes dynamically calculate the threshold for every message.

IV. Simulation and Performance Evaluation

A. Scenario and Parameter Settings

Simulations and evaluation of OSDR are implemented in ONE (Opportunistic Network Environment) [6], which is specially designed for opportunistic networks. In order to simulate real life opportunistic networks, we introduce the data set provided by the cabspotting project [7]. This data set [8] records more than 500 taxis for 30 days in San Francisco and each taxi reports the location every 60 seconds. We select different time in data set as simulation seeds to ensure simulation difference if we want to do experiment several times. Other parameters are set in TABLE I

We compare OSDR with Epidemic, SprayAndWait and Prophet. Comparison metrics include delivery rate, forwarding cost, and average delay: Delivery rate = number of delivered messages/number of all messages; Forwarding cost (overhead ratio) = (number of forwarding – number of delivered messages)/ number of delivered messages; Average delay = the mean time of the messages delivered from the source node to the destination node.

TABLE I
Settings of Simulation Scenario

Parameters	Value
Number of Node	100-500
Transmit range(m)	30
Transmit speed(MBps)	10
Buffer size(MB)	5-50
Message size(KB)	500-1024
Message creation Interval(s)	30
Message time to live(h)	333
Simulation time(h)	333

B. I.i.d assumption explanation of random variable T_N

Firstly, we illustrate the random variables T_N in each slot satisfying the identical distribution. We set time-slot to be consistent with performance evaluating experiment. We run 20 slots each time and repeat the experiment 10000 times. Through statistical data of a given node in each time slot, we can conclude that T_N substantially have the same distribution. Fig. 4 shows the cumulative distribution of T_N in three

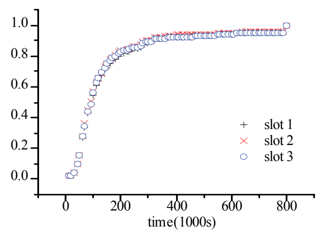


Fig. 4. Distribution of T_N.

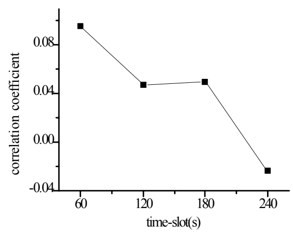


Fig. 5. Correlation of T_N.

arbitrarily selected slots of node 1. Then we use the Matlab software to calculate the correlation of adjacent T_N and find that all correlations are low. Fig. 5 gives the relationship between correlation of two adjacent slots and slot length. The figure indicates that when slot length is over 120s, correlation will be fairly low.

C. Global information of V_m and partial V_m' comparison

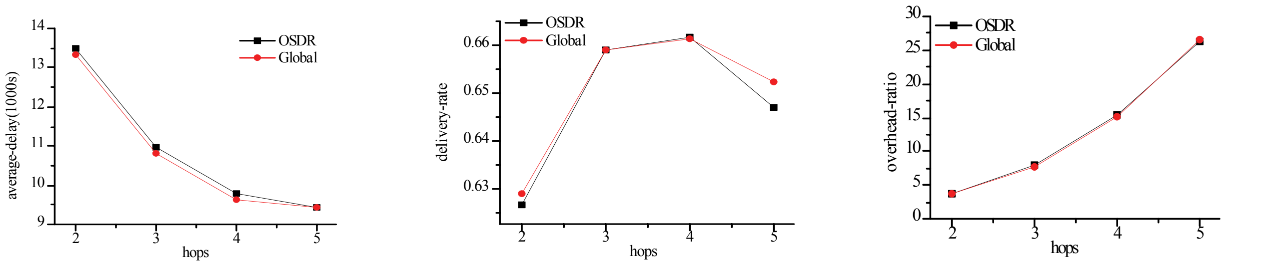
We evaluate the performance comparison between knowing the global information V_m and partial information V_m'. Results show in Fig. 6 and abscissa is the hop count limitation. These two cases have very similar results in delay, delivery rate and overhead. These demonstrate that although we cannot get the global information V_m for accurate calculation, using the partial information can still reach a result as good as the global one.

D. Slot length influence on OSDR performance

We then evaluate the influence of slot length on OSDR performance. We can see in Fig. 7 that these three metrics perform better as slot length decreases. That's because there are great opportunities that we may lose the best forwarding opportunities due to fewer observations in larger time slot. Considering the data gathering cycle is 60s and choices of time-slot will greatly influence the calculation cost, we choose length of 60 seconds as time-slot length in OSDR algorithm.

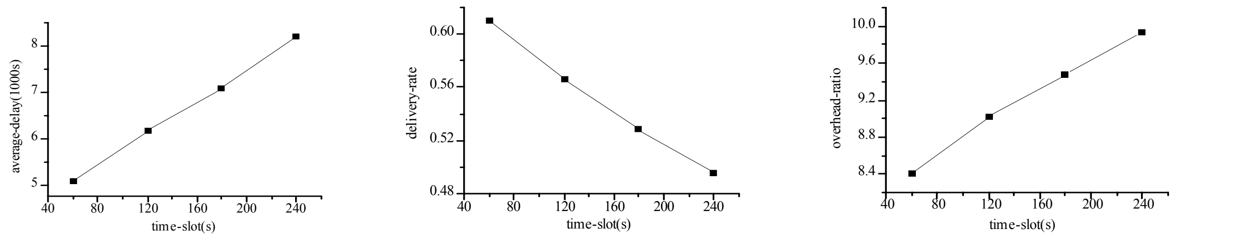
E. Buffer size influence on OSDR performance

We evaluate OSDR performance with different buffer limitations. The number of nodes is set to 500 and the hop count



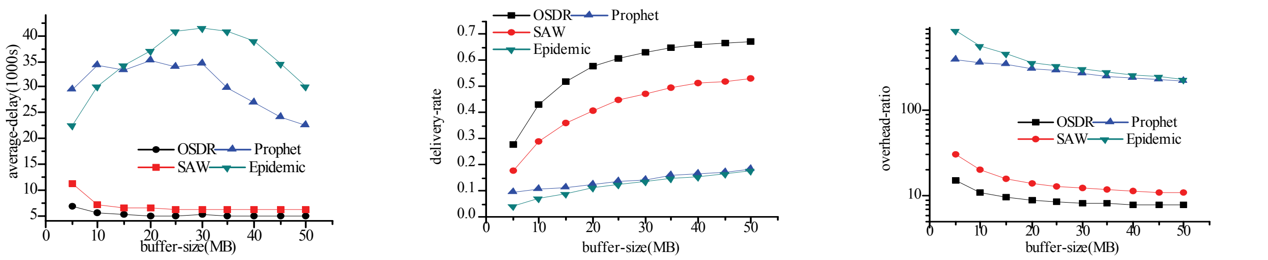
(a) (b) (c)

Fig. 6. Performance comparison between knowing V_m and V_m'



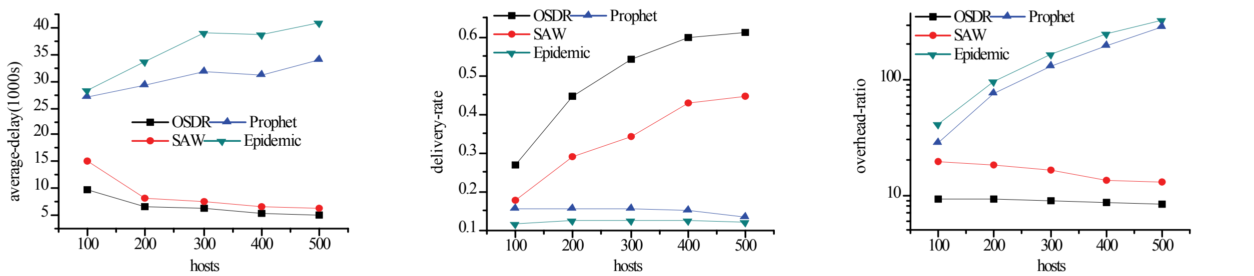
(a) (b) (c)

Fig. 7. Slot length influence on OSDR



(a) (b) (c)

Fig. 8. Buffer size influence on OSDR



(a) (b) (c)

Fig. 9. Network size influence on OSDR performance

is 3. Fig. 8 clearly shows that OSDR performs better than three other algorithms in all three metrics. SprayAndWait is near to OSDR in delay and overhead but have a delivery rate lower than OSDR for 10~ 20 percentages because it adopts greedy strategy: replicate as soon as it meets other nodes. This leads to fast speed replication but the nodes that OSDR selects have higher utilities.

F. *Network size influence on OSDR performance*

At last we evaluate performances in different network size. Buffer size is set to 25MB and hop count is 3. From Fig. 9 network performances degrade in Epidemic and Prophet with the nodes increasing. SprayAndWait and OSDR use the same copy limitation, so when the node density increases, their performances get promoted. And OSDR delivery rate is obviously higher than SprayAndWait. This advantage increases with network size expansion.

V. Related Works

Routing schemes in opportunistic network can be classified into several types. The most typical one is flooding scheme. Protocols [2][3][9] just do the replication without any selections, which will greatly degrade the performances when buffer size is limited and network size expands. But OSDR can promote network performances because network expansion can bring higher probability of choosing high utilized nodes. Another one is prediction based scheme. [4][10] are such kind of protocols. Prophet [4] updates the meeting probability every time the node meets another node. And OPF [10] uses the exponential distribution of meeting probability with inter-meeting time [11]. But recent study [12] has shown that the meeting probability is close to a power-law distribution in real life traces. And [11] has also proved in its testbed deployment that the meeting probability is affected by many factors. So, prediction-based scheme is impractical due to inaccurate predication of meeting probability. Recently many social-based routing protocols [13][14] have been proposed. Bubble [13] builds up cumulative contact length for community detection, but does not explore weights for data transmission. SDM [14] overcomes this deficiency but we can see that many nodes in real world like taxi cars do not have the society property. Therefore, building the contact pattern may lose effect in some cases.

Some other ideas like us are also proposed. They [15] [16] both want to optimize some performance by mathematic modeling. [15] uses optimal control theory to decide when to forward the message. It can only give the solutions to epidemic [2] and two-hops [17] routing while OSDR can be implemented on all routing frameworks. [16] applies the solutions to classical secretary problem [15] to select the best node. Every selects a higher utilized node to forward message and both of these two nodes' utility of this message become the higher one. Literature [5] has proved that the probability of obtaining the best node is just approximately e^{-1} . But OSDR avoids the low probability because it uses the average meeting time of all nodes to decide which nodes should be selected.

Optimal stopping method has attracted much attention in network performance optimization. Cai [18] proposes an optimal stopping based channel access method that can achieve higher network throughput. She helped a lot for this paper.

VI. Conclusion

In this paper, we have proposed an optimal stopping based routing algorithm. We define a rewarding function according to delay distribution for every slot and calculate the threshold according to stopping rules. Replication work will be done once the delay of the meeting node is lower than the threshold. This algorithm overcomes blindness of replication and reaches a comprehensive better performance in delay, delivery rate and network overhead.

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